Internal Insulation of Masonry with and without Hydrophobization in Inhabited Dwellings

Panagiota Pagoni, MSc **Eva B. Møller, PhD** **Tessa K. Hansen, PhD**

ABSTRACT

A large part of the European buildings were built from 1850 to 1960; a period when there was minimal focus on energy savings. Simultaneously, the facades of many of these buildings are worthy of preservation, so for additional insulation only internal thermal insulation is an option; despite various cases of mold issues in the intersection between the insulation and the wall. For insulation materials to be generally accepted, they have to be tested in reality to prove their efficiency and moisture safety to ensure the construction's robustness and the inhabitants' well-being. The present paper describes two case studies consisting of two residential building complexes in which the same type of diffusion open insulation material was applied in several apartments. In one of the cases, internal insulation was applied in combination with and without hydrophobization of the masonry. The performance of the two cases was determined by measurements of temperature and relative humidity at the intersection between insulation and masonry and in the indoor climate. Furthermore, the risk of mold growth was determined. The project investigated the conditions of the wall in relation to the masonry and insulation thickness, orientation of the wall, the impact of hydrophobization, and internal moisture load. Most measurements showed no risk of critical mold growth since the Mold Index did not exceed 2 in the wall interfaces. Exception to this appeared to be areas with thin masonry, high insulation thickness, or high indoor moisture load (more than humidity class 2). Surprisingly, the hydrophobization was most effective in the orientation with the least wind-driven rain. Finally, it was shown that a hydrophobized area with higher exposure to runoff faces harsher conditions than the one with high direct wind-driven rain.

INTRODUCTION

A vast part (41%) of the Danish residential buildings were constructed in the period from 1850-1960 (Hansen and Peuhkuri 2020). These buildings consist of multiple floors and their external walls are commonly made of solid masonry with embedded wooden beam ends (Hansen and Peuhkuri 2020). Changes to the exterior appearance should be avoided as many of these older buildings are valued for their historical, local, cultural and/or aesthetic values (Soulios et al. 2020; Hansen and Peuhkuri 2020). Therefore, adding extra insulation is only possible from the inside. However, it is risky since it leaves the original wall cold and exposed (Jensen et al. 2020; Brandt 2013), and the steep temperature gradient through the insulation yields possible condensation at the interface between insulation and the cold, external wall. This study aims to test this in real life by measuring and analyzing the hygrothermal conditions at the interface between internal insulation and solid masonry in two cases with internal insulation. In one of the cases, the effect of hydrophobization was also investigated. Additionally, mold growth models were used to assess whether the hygrothermal conditions are likely to initiate mold growth.

Internal Insulation

Internal post-insulation in cold climates causes the temperature to drop severely in the original wall, resulting in a colder

Panagiota Pagoni and Eva B. Møller are PhD Candidate and professor, respectively, at the Department of Civil and Mechanical Engineering, Technical University of Denmark, Kongens Lyngby, Denmark. **Tessa K. Hansen** is assistant professor at the Department of the Built Environment, Aalborg University, Copenhagen, Denmark.

external wall in the winter (Hansen and Peuhkuri 2020; Soulios, et al. 2021; Hansen, et al. 2018; Odgaard, et al. 2018a). Along with the decreased drying potential due to covering a surface, this effect leads to increased moisture content of the wall. Thus, moisture-related problems can occur, like frost damage at the exterior surface or rot in embedded wooden beam ends. Furthermore, interstitial condensation between internal insulation and existing wall can cause mold growth (Soulios et al. 2020; Hansen, et al. 2019; Odgaard, et al. 2018b; Jensen, et al. 2020). In the present study, the used insulation material is capillary active and vapor open. Therefore, the absorbed moisture can be redistributed and evaporate when conditions allow it (Hansen, et al. 2018). However, capillary active insulation materials must be fully bonded to the external wall to avoid air pockets behind insulation, where favorable mold growth conditions can occur.

Moisture

The external moisture loads can be found as vapor in the form of humidity and as liquid in the form of wind-driven rain (WDR) (Hansen, et. al 2018). WDR, is one of the most important parameters, especially for facades with porous materials, such as brick and mortar, as in the case studies of this project (Jensen, et al. 2020; Odgaard, et al. 2018b; Hansen, et al 2018). The amount of penetrating WDR depends on the pressure and capillary forces of the porous building materials (Hansen, et al. 2019), on solar radiation that can transfer the moisture deeper into the wall (Hansen and Peuhkuri 2020) (summer condensation), as well as the tightness of the joints, bricks, and render. The materials are more susceptible to WDR if there is a passage where the air pressure can force water into the wall (Hansen, et al. 2019). External rain protection like hydrophobization may positively affect the moisture conditions in older masonry as it may obstruct, or at least limit, the penetration of the precipitation. An effective hydrophobization treatment blocks the capillary suction without effecting the vapor diffusion of the wall, however, in some studies (Jensen, et al. 2020; Jensen, et al. 2020), the combination of hydrophobization and internal insulation in solid masonry walls showed that moisture was accumulated in the intersection of the wall and the internal insulation in cases with diffusion open insulation systems.

Mold

Favorable conditions for mold growth include high humidity levels and accessible nutrition elements. Thus, WDR penetration and the absence of adequate indoor heating lead to cold, damp surfaces, where high relative humidity (RH) conditions could lead to mold growth ("WHO" 2009). Although removing all wallpaper, including glue, limits the mold risk, dust can be sufficient nutrition for mold growth. The problems that mold may cause are connected to human health e.g. aggravating asthma, allergies or toxins affecting the respiratory system ("WHO" 2009). Jensen (Jensen et al. 2021) investigated some typical VOCs (Volatile Organic Compounds) that are produced by fungal growth and their ability to be transported to the indoor climate by diffusion through internal insulation. The VOCs were found to be able to diffuse through the insulation, and the ability is related to the vapor permeability (Jensen et al. 2021). Thus, the higher the water vapor permeability resistance of an internal insulation material, the less VOCs can transport to the indoor environment.

METHOD AND MATERIALS

Case A

Case A is a three-story residential building block located in the south-western part of Copenhagen, built in 1952-1962, with yellow multi-hole bricks and concrete slaps as floor partitioning (Hansen and Peuhkuri 2020). In the summer of 2015 the external walls of three north-facing gable apartments above each other were internally insulated with 80mm (3.15in.) mineral insulation boards (Hansen and Peuhkuri 2020). Figure 1 shows the façade and the top view of the building, and as can be seen, a small part of the gable is covered by the neighboring property. Sensors measured temperature and RH. Figure 1 also shows the location of 8 sensors in each apartment; all sensors were placed at the intersection between the insulation and the original wall. Some areas contained two sensors; one close to the floor and the other approximately in the middle of the wall's height (Hansen and Peuhkuri 2020). There are also sensors in the 1st floor that measured the indoor moisture content (moisture excess, g/m^3 or gr/gal). The humidity classes were determined according to the international standard EN ISO 13788 (ISO 2012). The measurements of the hygrothermal conditions started in winter 2015 and were reported until summer 2020 (Hansen and Peuhkuri 2020).

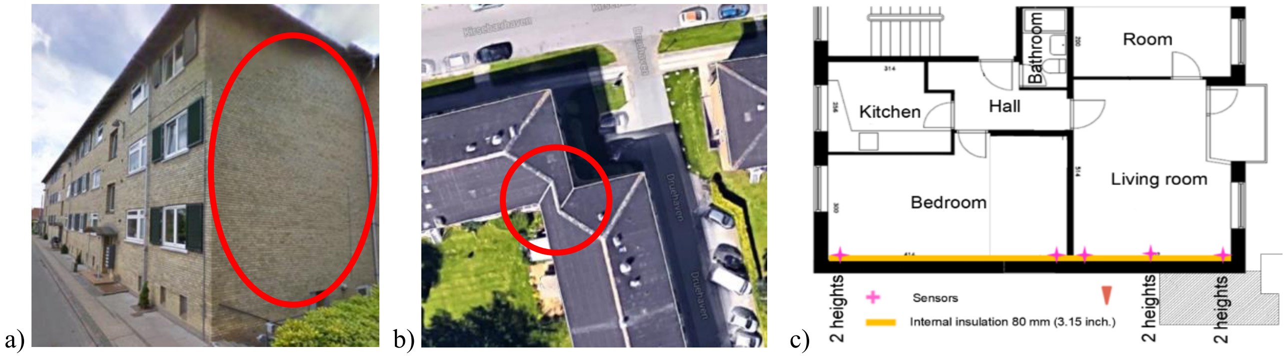


Figure 1 Case A: a) North insulated façade, b) Top view of the building showing the covering of the neighboring property, c) Floor plan with the locations of the insulation and the sensors (Hansen and Peuhkuri 2020).

Case B

Case B is located in the north-western part of Copenhagen, approximately 8km (5mi.) Northeast of case A. This case included five multi-story buildings in a large residential area built in 1940 (Janssen et al. 2020). The apartments were in different, but identical blocks, built at the same time for the same client (Janssen et al. 2020). One external gable wall of each test apartment, four gables in total (two north faced and two south faced) (Janssen et al. 2020), were internally insulated with 100mm (4in.) (220mm (8in.) for the spandrels) of the same mineral board insulation system as case A. One uninsulated apartment was used as reference. Two of the four gable walls, one per orientation (north and south), were treated with hydrophobization (Janssen et al. 2020). Figure 2 shows the gables and the floor plan with highlighted the sensors' locations. The indoor hygrothermal conditions were measured with two sensors (one in each room), and the conditions of the interface between the original wall and the insulation material were measured with three sensors, one at the spandrel and two in the middle of the external wall (Janssen et al. 2020). Sensors in bedrooms and living rooms measured the indoor moisture content (moisture excess, g/m^3 or gr/gal). The humidity classes were determined according to the international standard EN ISO 13788 (ISO 2012). The measurements started during autumn 2018 and were completed in summer 2020 (Janssen et al. 2020). Table 1 presents the information on the five case apartments.

Figure 2 Case B: a) Facade of all four gable walls with the test apartments highlighted (Janssen et al. 2020). b) Sensor placement on floor plan. Green-indoor climate, Red-interface, Yellow-insulation.

Table 1. Cases, Including the Time of the Set up (Janssen et al. 2020).

Apartment	Floor	Orientation	Hydrophobization	Internal insulation system
A1	3rd	N	Yes (mid Sept-18)	Yes (start/mid Oct-18)
A2	2nd	S	Yes (mid Oct-18)	Yes (start Oct-18)
A3	4th	N	No	Yes (mid Sept-18)
A4	5th	S	No	Yes (start Nov-18)
Reference	2nd	S	No	No

Construction

Existing Materials. In both cases, the original wall comprised of 1 ½ brick (360mm (14in.)) thick masonry (Hansen and Peuhkuri 2020; Janssen et al. 2020). In case A, the wall was multi-hole brick on the outside and lightweight clinker concrete at the backside (half and half). In case B, the thickness at the spandrel is only 1 brick (228mm (9in.)) (Janssen et al. 2020). In both cases, it is assumed that the bricks and mortar have approx. the same properties. Before the insulation, the gable walls in both cases had internal plaster and wallpaper and were blank externally (Hansen and Peuhkuri 2020; Janssen et al. 2020).

Insulation System. The same insulation system with different insulation thicknesses was studied in the two cases. The insulation system was autoclaved, mineral, inorganic boards made of low density aerated lightweight concrete, with a different porosity and pore size distribution than traditional aerated concrete (Hansen and Peuhkuri 2020; Janssen et al. 2020). The material was a diffusion-open insulation material installed without a vapor barrier. The complete insulation system was applied as fully adhered to the original external wall and is comprised of the following layers: Glue mortar-Mineral insulation boards-Finishing layer 4mm (0.2in.) (with reinforcement mesh and diffusion open paint) (Janssen et al. 2020). In both cases, the insulation system was installed after cleaning the wall by removing the existing plaster, wallpaper, and paint. In Table 2, the material parameters are presented according to DTU's experimental tests and (Janssen et al. 2020; Multipor and Insulation, n.d.). The hygrothermal material paramenters stay fixed over the whole moisture content range throughout the years.

Table 2. Material parameters and hygrothermal properties of the original wall and the insulation.

Material parameter	Brick	Mortar	Lightweight clinker concrete	Insulation	Glue mortar
Dry density [kg/m^3, lb/ft^3]	1774 [110.9]	1783 [11.4]	700 [43.8]	85-95 [5.3-5.9]	~770
Open porosity [m^3/m^3, ft^3/ ft^3]	0.363	0.329	-	-	-
Thermal cond. [W/mK, Btu·in/h·ft^2·°F]	0.761 [5.3]	0.839 [5.8]	0.37 [2.5]	0.042 [0.3]	0.18 [1.3]
Vol. heat capacity [J/m^{3}K, Btu/ ft^3·°F]	1.52*10^6 [22.6]	0.948*10^6 [14.1]	-	-	-
Water vapor dif. resistance factor μ	-	-	2	2	≤10
Water absorption coef. [kg/m^{2}s$^{0.5}$, lb/ ft^2·s$^{0.5}$]	0.199 [0.04]	-	-	-	-

Hydrophobization. In case B, the façade was renovated prior to hydrophobization. The renovation included replacing broken or damaged bricks, grinding the bricks' surface for smoothing, and repointing the joints (Janssen et al. 2020). The repointing was integrated by scratching approximately 20mm (0.8in.) of the old joints and refilling with lime-cement mortar (Janssen et al. 2020). After letting the walls dry for two weeks, the hydrophobization product was applied in one layer with a roll brush, following the manufacturer's recommendations (Janssen et al. 2020). The hydrophobization agent was silane-based, water-based, in 40% concentration cream (Janssen et al. 2020).

Measurements

The information on the sensors in both cases can be seen in Table 3, based on (BMT instruments Hygro-I T/RF n.d.; Lascar electronics n.d.; Hansen and Peuhkuri 2020) for case A and (Janssen et al. 2020; Onset 2020b. HOBO U12-012 Data Logger data sheet; Rotronic 2019; Weather 2012) for case B. Moisture content in the materials was not measured as focus was on the calculation of risk of mold growth. For this temperature and RH are the decicive parameters.

Table 3. Sensors' information for both cases.

Case building	Sensor type	Accuracy of sensors	Logging interval	Area of placement	Measuring condition
Case A	Hygro-I T/RF	±0.3°C and ±1.8% RH	30 min.	Interfaces	T, RH
	Lascar EL USB 2+	±0.45°C and ±2.05% RH	30 min.	Indoors,Outdoors	T, RH
Case B	Rotronic HL-RC-B with HC2A-S	±0.1°C and ±0.8% RH	1 hr.	Interfaces	T, RH
	HOBO data logger (U12-012)	±0.35°C and ±2.5% RH	1 hr.	Indoors	T, RH

Mold Model

The WUFI Mold index VTT 2.0, as described in (Ojanen et al. 2010; Hukka and Viitanen 1999), was used to predict the risk of mold growth based on temperature and relative humidity datasets. The sensitivity class "medium resistant" is used, corresponding to cement-based materials, and the material class is defined as having a relatively small decrease during periods of unfavorable mold conditions (Hansen and Peuhkuri 2020). The Mold Index M, as described in (Ojanen et al. 2010; Hukka and Viitanen 1999), (Viitanen et al. 2015), classifies the mold growth level in a spectrum from 0 (no growth, spores not activated) to 6 (very heavy and tight growth, coverage around 100%).

RESULTS

In Situ Measurements of Temperature and Relative Humidity

Case A. The measurement results of case A are presented in Fig. 3a, 3b, 3c. There is a 3 month period in 2017 where the measurements stopped due to malfunction of the sensors (Hansen and Peuhkuri 2020). Where the gable is attached to the neighboring building, the wall is considered as an internal wall, so the sensors there measured approximately indoor climate conditions (Hansen and Peuhkuri 2020). However, there were sesnsors dedicated to the measurement of indoor climate. The measurements in the interface between insulation and the existing wall against outdoor climate were generally below 80%. The measurements varied between 50-80% with seasonal variation, where the highest values were measured during cold months. Measurements from the 1st floor derivated from the above; in the eastern bedroom sensors 64105 and 64106 showed higher values than the other measuring points, especially for the cold season 2019-2020. During this period, the RH in the interface was over 90%, and one sensor (64105) reached 100% for a few months before the RH decreased in the spring. Temperature registrations from these sensors also showed lower temperatures, especially sensor 64106 exhibited up to 5°C decrease in cold seasons compared to the rest of the sensors. Moreover, in sensor 64105 the RH increased for each winter season. On the other floors, 2nd and 3rd floor, RH is also higher in the eastern room compared to the western living room, but with smaller differences. Concerning the indoor moisture content, the 2nd and 3rd floor had a moisture load corresponding to humidity class 2 (dwellings with normal occupancy and ventilation) with some winter months that appear to be in humidity class 3 (dwellings with unknown occupancy density-rental dwellings). The 1st floor appeared to be in class 3 for a longer period throughout the year. In general, the moisture excess was up to 6 g/m^3 (0.35 gr/gal).

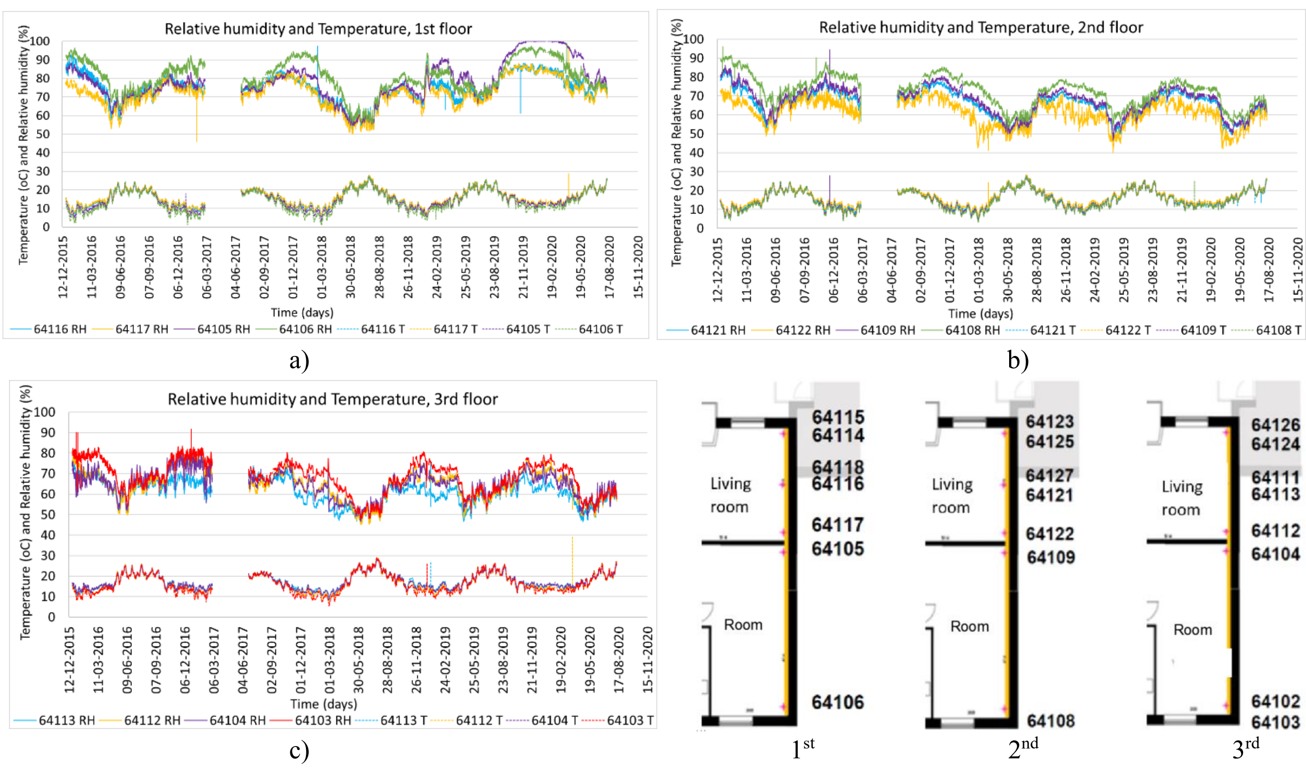
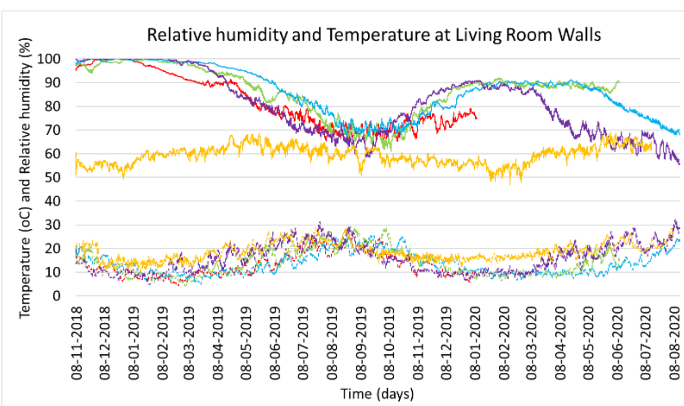


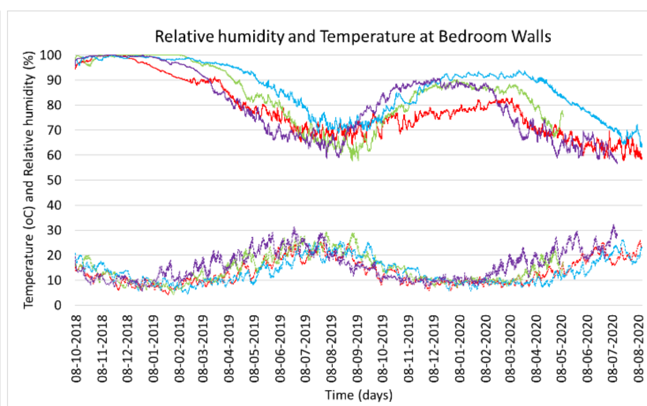
Figure 3 Measurement data from case A, on the a) 1st, b) 2nd and c) 3rd floor. For clarity reasons, in the places where there are 2 sensors in two different heights, only one of them is presented. Sensors 64115, 64114, 64123, 64125, 64126, 64124 which are located to the gable adjacent to a neighboring building are neglegted (Hansen and Peuhkuri 2020). Note: 0ºC=32ºF, 10 ºC =50 ºF and 20 ºC =68 ºF.

Case B. The results of the measurements for RH and temperature in the intersection between the original wall and the insulation for the living room, bedroom, and spandrels of case B are presented in Fig. 4a, 4b, 4c. The systems were not installed simultaneously and the drying phase had different offsets (Janssen et al. 2020). Also, the measurements of the reference apartment (yellow) must be regarded as measurements of the indoor climate since the sensor is mounted on the living room wall. In addition, some measurements stopped earlier than others due to malfunction of the sensors. The measurements in the interfaces ranged between 60-90% with seasonal variation, with the highest RH measured in winter. An exception appears to be the spandrels area, where RH was 100% for the first 9 months and minimum RH was almost 70% during warm months. In the winter 2019-2020 RH reached 100% again. Moreover, the sensor in A2 (south, hydrophobized) at the spandrels showed much more fluctuations in RH than the rest of the sensors. Apart from the spandrels, sensors in A3 (north, non-hydrophobized) in the living room and the bedroom were the ones that exhibited the highest RH most of the time, while A1 (north, hydrophobized) in bedroom and living room showed the lowest RH. In general, after the first months of relatively high RH, the RH in all sensors decreases and reaches 90% next winter, except for A1 that reached 80% the winter after installation. Regarding the indoor moisture load, apartments A1 and A2 seem to have an overall humidity class of 2. Apartments A3 and A4 appear to be in humidity class 3 most months of the year, and there was found the higher moisture excess which was up to 6 g/m^3 (0.35 gr/gal), as in case A.

Mold Index

The risk of mold growth for both cases (A and B) was assessed with the VTT Mold Index model (Ojanen et al. 2010; Hukka and Viitanen 1999). The Mold Index has been calculated for specific sensors, which have been selected based on either high registered RH (> 85%) or location. The risk is depicted in Fig. 5a, 5b. In case A, the highest mold risk was found in the most recent winter period for the 1st floor apartment. In specific there were two sensors in the bedroom on the first floor, sensor 64105 was the one that showed the maximum Mold Index of 2.7 (several local mold growth colonies on surface (microscope)) whereas sensor 64106 showed value below 1 (small amounts of mold on surface (microscope), initial stages of local growth). For the other locations, the calculated mold risk was equal to zero. For case B, the sensors in all locations in all apartments, except the ones at the spandrels, were found to have Mold Index 1 or less. All the spandrels' sensors showed higher values (Mold Index 2-3), with sensor A3_spandrels having the maximum value of 3 (visual findings of mold on surface, < 10% coverage, or, < 50% coverage of mold (microscope)). It has to be noted that although this mold model is created for free surfaces (surfaces in touch with air layer) it can also be used for inside structures. In that case, surfaces with a Mold Index below 2 are acceptable since they are considered to be on the safe side (Ojanen et al. 2011).





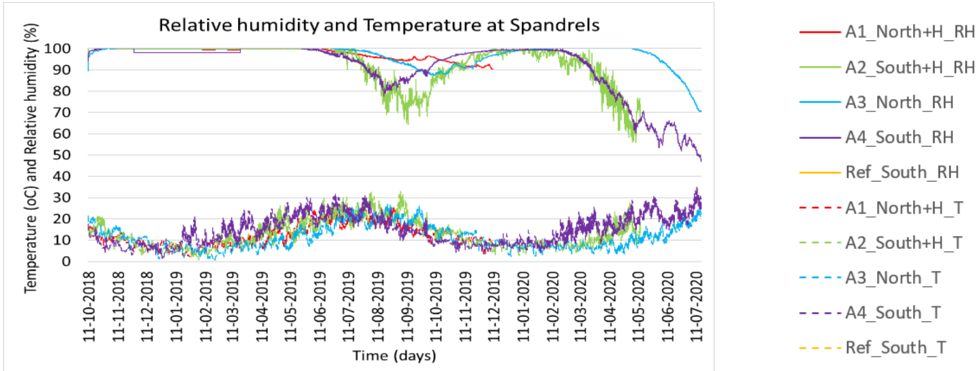


Figure 4 Measurement data from a) living room, b) bedroom and c) spandrels in Case B with apartments A1-red, A2-green, A3-blue and A4-purple and Reference-yellow. Note: 0ºC=32ºF, 10 ºC =50 ºF and 20 ºC =68 ºF.

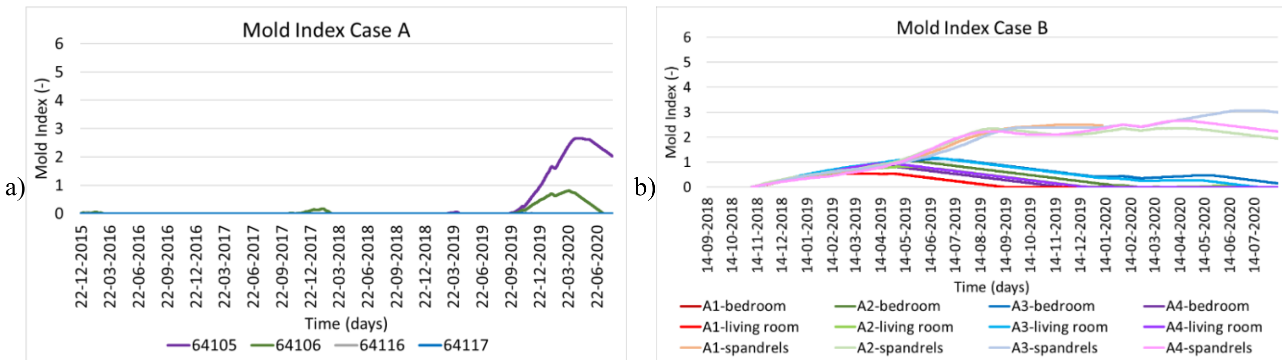


Figure 5 Mold index of some measurements from a) case A (all 1st floor) and b) case B.

DISCUSSION

Instead of measuring moisture content in the material, it was chosen to measure RH. This can lead to faulty results, especially when the material is very wet. However, in this case, RH was mostly lower than 90 %, and the measurements were therefore considered to be sufficiently accurate to describe tendencies.

As the insulation system is diffusion-open, the measurements in both cases follow the same trend; in winter, the RH in the interface between the internal insulation and the original wall increases and in summer decreases again. In order for the insulation system solution that is suggested in this study to be moisture safe it needs to be applied in climate regions with similar climate conditions as the temperate climate of Denmark (mild winters and cool summers). In case A, the north-facing gable was insulated with 80mm (3.15in.) of the insulation material, therefore, only little WDR and no sun-driven moisture were expected, and no solar radiation for drying the wall from the outside. Moreover, the eastern room, which was found to have increased RH, is located next to the kitchen, which could mean a high moisture load, especially if the exhaust hood was not used and there was no ventilation. This cannot be verified as there are no indoor climate measurements after 2017. But the measurements indicate that there is a limit to how much moisture this capillary active insulation material can transport back to the indoor climate.

In case B, the first winter period (2018-2019) was the period of drying out of the built-in moisture. In the following winter, the moisture level did not reach the level of the first winter, a tendency that the two upper floors in case A also showed. Hydrophobization seemed to positively affect the northern gable in the last 10 months of 2020, while zero or negative effect was noticed on the southern gable, which received the highest amount of WDR. This is surprising as Jensen (Jensen, Odgaard, et al. 2020) found that the effect of hydrophobization was most distinct in walls with much WDR. However, that was based on measurements with a controlled indoor climate and at ground floor level. Firstly, the north-facing A1 appears to have the lowest RH during all measurement period; hydrophobization in north-oriented walls (less WDR) seems to be an efficient combination. Secondly, south-facing A2 fluctuates between A3 (in the living room) and A4 (in the bedroom), which means that south-oriented walls may have the highest RH in some periods, which was expected due to the high WDR in that direction. Thirdly, north-facing A3 has always the highest RH; even though it is the northern wall that the absence of hydrophobization is obvious. In addition, floor differences seem to play a role. WDR is higher in A4 (no hydrophobization), which is on the 5th floor while A2 (hydrophobization) gets more runoffs, which is located on the 2nd floor. Therefore, because in most periods, the RH of A2 is higher than A4, WDR seems to be less important than the run off. Furthermore, the fluctuating results for the spandrels in A2 are explained by the radiator in that area which influences the wall's RH. In general, the extremely high RH of the spandrels could result from the combination of the high thickness of insulation (220mm (8in.)), which increases the wall's temperature with the decreased thickness of the wall (228mm (9in.)) which leads to higher risk of penetrating water.

In case A, the mold model confirmed that there is no risk of mold growth behind the insulation, again except for the 1st floor apartment. A Mold Index below 1 is generally assumed to be completely without risk, and for interfaces inside constructions without direct contact to the indoor air, a Mold Index of 2 is acceptable (Viitanen et al. 2015). The one sensor that exhibited RH of 100% in the most recent winter period exceeds this value and achieves a Mold Index of 2.7 before declining with the decreasing RH. Unfortunately, the indoor moisture load was only measured at the beginning of the period. The moisture level behind the insulation could indicate that the inhabitants changed behavior and the moisture excess therefore increased. For case B, the measurements show variable mold growth conditions. As Mold Index of 1 is assumed harmless, most of the places are also assumed moisture safe. However, at the area of spandrels, where the wall is thinner and the insulation thicker, there is an increased mold risk due to the combination of high RH and temperature. Also, because the mold model is developed for free surfaces, and despite the results of the mold model, there may not be any mold growth at the interface, both due to the lack of free surface and the high pH as described in (Jensen et al. 2021).

The similarities between the two cases are that in the two upper floors of case A and in the regular wall in case B, the RH decreased in the second winter and never reached the values of the first winter again. That is because the built-in moisture dried out during the first winter. However, the moisture level of case A was never as high as in case B probably because the measurements started almost half a year after the insulation application. Another common fact is that the maximum Mold Index was 3, although in case B we had multiple places where Mold Index was over 1. The main difference between the two cases is that the RH in case A reaches until 80% (except the 1st floor) while in case B it reaches more than 90%, this could be because of the thicker insulation in case B (100mm (4in.) and 80mm (3.15in.) in case A). In both cases, the risk of unacceptable mold growth was small; it only appeared in the spandrels and in one apartment where the indoor moisture load was likely to be high. Finally, if a perfect condition of the insulation being fully bonded to the wall is assumed, the area will be at the safe side in terms of mold growth behind the insulation and VOCs' penetration through the insulation material. However, if the wall thickness is too low (as in the spandrels) or the indoor humidity levels are too high, there might appear limited mold growth even in the perfectly adhered insulation case.

CONCLUSION

In the project, the same type of diffusion open, capillary active, internal insulation has been used in two different thicknesses in the two cases to determine if the system is moisture safe in real life. The system is considered moisture safe if the Mold Index, as defined by (Viitanen et al. 2015) is below 2 at the intersection between the original wall and internal insulation. The main conclusions are:

- The insulation system is moisture safe if: a) The interior moisture load corresponds to humidity class 2 in EN ISO 13788 (ISO 2012). b) The insulation thickness does not extend 100mm (4in.). c) The original wall is at least 1½ stone (360mm (14in.) All prerequisites must be fulfilled.
- Hydrophobization can lower the external moisture load, but the amount of runoff is more important than the direct WDR.

The results accumulated in this study could be considered reliable indications for practice. However, the limits given here are only based on these two cases and should be investigated further. Especially the influence of internal moisture load as this can be reduced by proper ventilation and the insulation thickness, as this is the variable parameter when a system is chosen.

ACKNOWLEDGMENTS

Acknowledgments go to the former SBi team (Danish Building Research Institute), who initiated the case A measurements in collaboration with the Municipality of Copenhagen, and 3B (KAB). Furthermore, thanks to Realdania and Xella for financial support, materials and craftsmanship in case B.

REFERENCES

Brandt. 2013. *Fugt i Byhninger, SBi-Anvisning 224, Statens Byggeforskningsinstitut, Aalborg Universitet.*

Hansen, Bjarløv, and Peuhkuri. 2019. "The Effects of Wind-Driven Rain on the Hygrothermal Conditions behind Wooden Beam Ends and at the Interfaces between Internal Insulation and Existing Solid Masonry." *Energy and Buildings* 196: 255–68. https://doi.org/10.1016/j.enbuild.2019.05.020.

Hansen, Bjarløv, Peuhkuri, and Hansen. 2018. "Performance of Hydrophobized Historic Solid Masonry – Experimental Approach." *Construction and Building Materials* 188: 695–708. https://doi.org/10.1016/j.conbuildmat.2018.08.145.

Hansen, Bjarløv, Peuhkuri, and Harrestrup. 2018. "Long Term in Situ Measurements of Hygrothermal Conditions at Critical Points in Four Cases of Internally Insulated Historic Solid Masonry Walls." *Energy and Buildings* 172: 235–48. https://doi.org/10.1016/j.enbuild.2018.05.001.

Hansen, and Peuhkuri. 2020. "Demonstrationsprojekt Om Indvendig Efterisolering i 3b's Afdelinger Druehaven 5 Og Folehaven 75. Build 2020. Slutrapport. (Delrapport 3)."

Hukka, and Viitanen. 1999. "A Mathematical Model of Mould Growth on Wooden Material." *Wood Science and Technology* 33 (6): 475–85. https://doi.org/10.1007/s002260050131.

ISO - International Standard Organization. 2012. "ISO 13788:2012 Hygrothermal Performance of Building Components and Building Elements - Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation - Calculation Methods." *Building Standard Institute*.

Janssen, Deckers, Vereecken, Feng, Soulios, Vanek, and Hansen. 2020. "RIBuild: Impact of Water Repellent Agents on Hygric Properties of Porous Building Materials," 159. https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32016R0679&from=PT%0Ahttp://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52012PC0011:pt:NOT.

Jensen, Bjarløv, Rode, Andersen, and Møller. 2021. "Laboratory-Based Investigation of the Materials' Water Activity and PH Relative to Fungal Growth in Internally Insulated Solid Masonry Walls." *Indoor Air*. https://doi.org/10.1111/ina.12796.

Jensen, Bjarløv, Rode, and Møller. 2020. "Hygrothermal Assessment of Four Insulation Systems for Interior Retrofitting of Solid Masonry Walls through Calibrated Numerical Simulations." *Building and Environment* 180. https://doi.org/10.1016/j.buildenv.2020.107031.

Jensen, Odgaard, Bjarløv, Andersen, Rode, and Møller. 2020. "Hygrothermal Assessment of Diffusion Open Insulation Systems for Interior Retrofitting of Solid Masonry Walls." *Building and Environment* 182. https://doi.org/10.1016/j.buildenv.2020.107011.

Jensen, Rode, Andersen, Bjarløv, and Møller. 2020. "Internal Insulation of Solid Masonry Walls - Field Experiment with Phenolic Foam and Lime-Cork Based Insulating Plaster." *E3S Web of Conferences* 172: 1–8. https://doi.org/10.1051/e3sconf/202017201003.

Odgaard, Bjarløv, and Rode. 2018a. "Influence of Hydrophobation and Deliberate Thermal Bridge on Hygrothermal Conditions of Internally Insulated Historic Solid Masonry Walls with Built-in Wood." *Energy and Buildings* 173: 530–46. https://doi.org/10.1016/j.enbuild.2018.05.053.

Odgaard, Tommy, Søren Peter Bjarløv, and Carsten Rode. 2018b. "Interior Insulation – Experimental Investigation of Hygrothermal Conditions and Damage Evaluation of Solid Masonry Façades in a Listed Building." *Building and Environment*. https://doi.org/10.1016/j.buildenv.2017.11.015.

Ojanen, Tuomo, Ruut Peuhkuri, Viitanen, Lähdesmäki, Vinha, and Salminen. 2011. "Classification of Material Sensitivity– New Approach for Mould Growth Modeling." ... *Nordic Symposium on* ... 2 (9): 867–74. http://webhotel2.tut.fi/nsb2011/sites/webhotel2.tut.fi.nsb2011/files/b10_02_tuomo_ojanen_vtt_nordic_9th_classification__mould_growth_final2.pdf.

Ojanen, Viitanen, Peuhkuri, Vinha, and Salminen. 2010. "Mold Growth Modeling of Building Structures To Improve the Model."

Soulios, Hansen, Feng, and Janssen. 2020. "Hygric Behavior of Hydrophobized Brick and Mortar Samples." *Building and Environment* 176 (March): 106843. https://doi.org/10.1016/j.buildenv.2020.106843.

Soulios, Hansen, and Peuhkuri. 2021. "Hygrothermal Performance of Hydrophobized and Internally Insulated Masonry Walls - Simulating the Impact of Hydrophobization Based on Experimental Results." *Building and Environment* 187 (September 2020): 107410. https://doi.org/10.1016/j.buildenv.2020.107410.

Viitanen, Krus, Ojanen, Eitner, and Zirkelbach. 2015. "Mold Risk Classification Based on Comparative Evaluation of Two Established Growth Models" 78: 1425–30. https://doi.org/10.1016/j.egypro.2015.11.165.

"WHO Guidelines for Indoor Air Quality : Dampness and Mould." 2009.